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Contents

List of Tables

List of Figures

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Experimentally Validated Predictive Models for Puffability Of Gelatinized Rice

DONALD E. GOODMAN[1] AND RAMU M. RAO[2]

Rice has been called the aristocrat of cereals, and is a major crop in the United States (*6*)[3]. The point can be convincingly argued that rice is the most important grain crop in the world. Over one-half of the world's population relies upon rice as the primary food source of both carbohydrates and protein.

Rice continues to be utilized as a direct table food. However, in the United States a substantial and increasing amount of the domestic rice crop is processed into numerous kinds of prepared products (*23*). Whole grain domestic rice is used in the preparation of ready-to-eat breakfast cereals (*4, 22, 23*), canned rice products (*7, 24*), and quick-cooking rice (*26*). Broken rice is utilized in the production of rice flours for baking (*25*), in the brewing industry (*10, 11*), and in producing fermented rice products (*41*).

Due to growing emphasis on the processing of milled rice, it becomes increasingly important to understand the effects and interrelationships that various physical, chemical, and mechanical properties of rice have on the "processability" of rice. Many of the physicochemical properties of rice that are directly related to the functional behavior of rice when it is subjected to various industrial processes are not well understood. It is generally recognized that expansion of rice involves the taking of a cooked (gelatinized), dried rice of 8 percent to 14 percent moisture and very quickly heating the rice to flash or to instantaneously vaporize the moisture within the rice grain. The rapid expulsion of the moisture and the surface drying or fixation of the surface structure results in an expanded product of high porosity. However, there is very little in the literature that quantitatively describes the physicochemical nature of puffing. There is ambiguity and even contradiction in the literature concerning the relationships that

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[3]Italic numbers in parentheses refer to Literature Cited, page 42.

might be found among those commonly measured physicochemical properties of rice. Consequently, the industrial buyer has no basis other than historical evaluation upon which to buy rice for puffing, nor is the rice breeder any better equipped to breed new varieties of rice that would exhibit milling, insect resistance, and puffing characteristics superior to those of currently availble varieties.

The objectives of this research were to (1) measure the values of selected physicochemical parameters for various rice samples taken from the Rice Uniform Regional Performance Nursery; (2) identify those properties influencing the hardness and puffing of rice, and (3) develop and validate regression equations for the prediction of kernel hardness and puffing of cooked rice.

Literature Review

Rice Quality

Prior to the mid-1950s, domestic rice quality was established by milling yields and cleanliness and purity of the crop (*45*). Due to the lack of a unified evaluation program to ensure the processing and utilization suitability of new varieties of rice, a coordinated rice breeding and testing program was established. This program is conducted cooperatively by the U.S. Department of Agriculture and the agricultural experiment stations in the rice producing states of Arkansas, California, Louisiana, Mississippi, and Texas. One of the primary objectives established for this program was the evaluation of all new varieties of rice to ensure, prior to release, that the new variety has the same or improved processing characteristics as the variety it is to replace (*45*).

It should be pointed out, however, that at the inception of this program an overwhelming percentage of the domestic usage of rice was attributed to the consumption of rice as a direct table food. Much of the rice utilized as processed rice was in canned soups. Thus, quality evaluations for processing suitability either related to the cooking of milled rice or its stability in canning operations.

A series of analyses were selected to be used in the coordinated rice breeding and testing program. These procedures measured specific chemical and physical properties of rice, which collectively served as standardized indicators of cooking and canning qualities of rice. The most commonly measured chemical properties were amylose (*14*), alkali spreading value (*21*), water uptake capacity (*9*), birefringence and end-point temperature (*8*), amylographic pasting (*9*), protein content (*37*), parboil canning stability (*74*), kernel hardness, and milling yields. The results of these tests aid rice breeders in selecting varieties that have both desirable agronomic and cooking qualities.

Little attention has been given to the special processing requirements of industrial utilizers of rice, such as the processors of breakfast cereals and convenience foods. The behavior of cooked rice as it is dried and then subjected to very quick, almost instantaneous changes in temperature and/or pressures has not been fully explained. There is a need among the industrial processors of rice to know how the various physicochemical properties of rice interact with their particular processing environments (*4*, *7*, *10*, *11*, *22*).

Physicochemical Interrelationships

Most measures of rice quality relate to either the amylose content of the rice kernel or the gelatinization temperature of the rice. Reports by Rao et al. (*30*), Juliano et al. (*19*), Webb et al. (*47*), and Webb and Steimer (*48*) indicated that amylose content of rice is considered to be the single most important characteristic in the determination of cooking and eating quality of rice. Chang and Parker (*5*) noted that amylose content, gelatinizing temperature, gel consistency, protein content, and aroma of the rice were the important properties that affected the cooking qualities of rice.

Halick and Kelly (*9*) reported that gelatinization temperature of rice could be positively correlated with the time required for cooking. They further noted that gelatinization temperatures were not correlated with amylose content, but that amylographic peak viscosity and set-back (gel formation on cooling) or retrogradation were correlated with amylose content.

During their studies on steeping of corn, Watson and Sauders (*43*) found that a protein matrix holds the starch granules together in the corn endosperm. This may relate protein content to the gelatinization temperature of starch, although this aspect was not discussed in their work.

Beachell and Stansel (*3*) found no clear relationship between gelatinization temperature and amylose content, which corroborated the earlier work of Halick and Kelly (*9*). Beachell and Stansel (*3*) classified rice by gelatinization temperature, i.e. low gelatinizing rice had a gelatinization temperature range of 62° to 69°C, intermediate types gelatinized between 70° and 74°C, and high gelatinizing rice had gelatinization temperatures between 75° and 80°C. They noted that varieties classed as low gelatinizing types were not suited for parboil canning or for quick cooking.

Amylose content was used by Webb (*44*) to classify domestic long-grain varieties of rice as ''hard'' rice due to the typically high amylose content of these varieties. Domestic medium- and short-grain varieties, with typically lower amylose content, were collectively referred to as ''soft'' rice.

Juliano et al. (*17*) found that among 16 nonwaxy (containing no amylose) varieties of rice there was no significant correlation between gelatinization temperature and amylose content ($r = -0.103$) or protein content ($r = -0.07$). However, by removing two anomalous varieties from the sample set, a significant positive correlation resulted between gelatinization temperature and amylose content (r= +0.63, n = 14). They also found a highly significant positive correlation between amylographic setback (the difference between final viscosity at 50°C and the peak viscosity) and amylose content (r = +0.78).

Juliano et al. (*18*), in another study with 55 varieties of rice, found no correlation between amylose content of nonwaxy rice samples and gelatinization temperature (r = −0.103), nor could a significant correlation between protein content and gelatinization temperature (r = −0.087) be found. These workers found a strong negative correlation between gelatinization temperature and alkali spreading value (r = −0.781. No significant correlation was found between either amylose content of the milled rice and the length-to-width ratio of rough rice (r = +0.089) or the protein content of the milled rice and the length-to-width ratio of rough rice (r = +0.018). Based on this, it was concluded that kernel dimensions were not useful indices of the chemical composition of the rice kernel.

In this same study it was observed that the drop in amylographic viscosity on cooking to 94°C relative to peak viscosity was negatively correlated with amylose content (r = −0.444) and was not correlated with protein content (r = −0.055). The drop in viscosity was generally related to the degree of disintegration of the starch granules. The final viscosity at 94°C was found to be positively correlated with amylose content (r = +0.716) while being negatively correlated with protein content (r = −0.349). Finally, the degree of setback, or retrogradation, was highly significant for amylose (r =+0.734) but not for protein (r = −0.174).

Reyes et al. (*31*), while investigating the differences in starch composition of 10 nonwaxy and four waxy varieties of rice, each with different eating and cooking qualities, were unable to correlate amylose or protein content with gelatinization temperature. Moreover, no correlation was indicated between amylose intrinsic viscosity and gelatinization temperature, nor was it possible to correlate starch granule size with gelatinization temperature. It was concluded that the micellar structure of the individual starch granules was of importance in explaining the varietal differences in gelatinization temperatures. This view was supported by the work of Sterling (*35*) on the microcrystalline structure of starch grains. Schoch (*34*) stated that the behavior of starch, in general, was based primarily upon two factors: (1) the presence, properties, and spatial conformations of the two starch fractions (linear amylose and branched amylopectin), and (2) the formation of amylose and amylopectin into micelles. Wurzburg and Szymanski (*50*) explained the elasticity of starch granules, as manifested by reversible swelling during water absorption, in part as a result of the intermicellar regions of the granules.

In their report on the relationship of starch, protein, and gelatinization temperature to cooking and eating qualities of milled rice, Juliano et al.

(*19*) studied 23 nonwaxy and one waxy variety of rice. The amylose content of the nonwaxy varieties ranged from 15.9 percent to 32.6 percent (dry basis), while the waxy variety was reported to have 3.9 percent (dry basis) amylose. The protein content of all varieties ranged from 6.64 percent to 16.48 percent (dry basis). Again, there was an inability to correlate gelatinization temperature with either protein ($r = +0.296$) or amylose ($r = -0.116$). The amount of swelling or expanding of the rice kernel during cooking was found to be slightly positively correlated with amylose content ($r = +0.378$). Cooking time, or time for complete gelatinization, was found to be significantly correlated with protein ($r = +0.648$). Additionally, there was a very high negative correlation ($r > -0.7$) between amylose content and eating qualities of rice such as tenderness, cohesiveness, and color. Although definitive correlations of processing attributes with rice protein content had yet to be established, it was noted in this study that high-protein rice tended to have a creamier appearance, and it was shown that high-protein rice had longer cooking times and lowered water absorption capacity.

In the study on the quality of milled rice, Juliano (*15*) found that both amylose and protein content of samples of the same nonwaxy variety varied by as much as 6 percent from sample to sample. He further indicated that in general there was no direct relationship between rice amylose content and gelatinization temperature, while also pointing out, however, that there had been no reported rice varieties having both a high amylose content and a high gelatinization temperature. In addition, this study verified a correlation between alkali spreading value and gelatinization temperature range, as earlier reported by Little et al. (*21*) and Juliano et al. (*18*).

In subsequent work on the physicochemical properties of the rice grain, Kongseree and Juliano (*20*) found no significant correlation between gelatinization temperature and amylose ($r = -.038$) or protein. However, a highly significant correlation was found between gelatinization temperature and alkali spreading value ($r = -0.96$). Additionally, there was no significant correlation between amylose content and hardness ($r = -0.4$). These results verified previously reported data. Based on these data, and in agreement with others Kongseree and Juliano noted that presumably the differences in the gelatinization temperatures of starch were due to properties of the whole endosperm, reflecting the degree of porosity of the kernel.

Another physicochemical parameter of the rice kernel of interest to the industrial rice processor is the hardness of the rice kernel. As used in rice technology, kernel hardness represents more than merely the measure of kernel surface resistance to penetration, but rather is a measure of the compressive shear strength of the rice kernel. Hardness is measured by orienting a rice kernel on its flattest surface between two parallel plates (the rice major axis is parallel to the plates) and exerting a force at constant speed until the kernel fractures or yields. The force in pounds or kilograms required for kernel failure is measured and reported, or is converted to the modulus of resilience (the measure of the energy required to deform a grain kernel to its yield point) of the kernel. Zoerb and Hall (*51*) reported that moisture content had the greatest influence on the strength properties of grains. Juliano (*13*) found that kernel hardness of rice was significantly correlated to protein content. Pomeranz and Meloan (*29*) indicated cereal grain kernel hardness appeared to be related to both protein and moisture content.

Many of the interrelationships of the chemical, physical, and physicochemical properties of the rice kernel were summarized by Juliano (*12*). Additionally, this report contains a tabulation of the proximate and detailed chemical analyses of many world-wide varieties of rice.

Materials and Methods

Samples of rice were selected from commercial as well as experimental varieties of short-, medium-, and long-grain types, from four different geographic locations, over a 2-year priod. These samples of rough rice were hulled and milled. The milled rice samples were analyzed for moisture and hardness. The physical measurements, including length, width, area, volume, and hardness of the milled samples, were determined. The milled samples were analyzed for amylose and protein content as well as alkali spreading value. Finally, these samples were cooked, air dried, and puffed in hot oil. A random selection of approximately 70 percent of these samples was chosen and used to generate a predictive multiple regression equation for the degree of puffing. The model was validated using the remaining 30 percent of the samples. Additionally, a model was generated describing the hardness characteristic of these samples.

Selection and Procurement of Samples

Requests were made to the rice experiment stations in Arkansas, Louisiana, Mississippi, and Texas for samples of various short-, medium-, and long-grain experimental and commercial varieties of rice from the 1979 and 1980 crops. Rough rice samples from each station were received individually packaged in paper bags, each properly labeled. All rice samples included in this study are identified in Table 1; the number of samples of each grain type used in this investigation is shown in Table 2.

Preparation of Samples

The preparation of samples consisted of initially determining the moisture content of the rough rice, followed by hulling, milling, and grading resulting in white, head rice samples to be used in subsequent investigations. These steps, outlined in Figure 1, were done in strict accordance with the U.S. Department of Agriculture Inspection Handbook (*39*).

Table 1.—Sample number, variety, year, location and grain type of all rice samples used in the investigation

Sample number	Variety	Year	State	Grain type
1	Mars	1979	Arkansas	Medium
2	Mars	1979	Texas	Medium
3	Mars	1980	Arkansas	Medium
4	Mars	1980	Texas	Medium
5	Mars	1980	Louisiana	Medium
6	Mars	1980	Mississippi	Medium
7	Nato	1979	Arkansas	Medium
8	Nato	1979	Texas	Medium
9	Nato	1980	Arkansas	Medium
10	Nato	1980	Texas	Medium
11	Nato	1980	Louisiana	Medium
12	Nato	1980	Mississippi	Medium
13	Saturn	1979	Arkansas	Medium
14	Saturn	1979	Texas	Medium
15	Saturn	1980	Arkansas	Medium
16	Saturn	1980	Texas	Medium
17	Saturn	1980	Louisiana	Medium
18	Brazos	1979	Arkansas	Medium
19	Brazos	1979	Texas	Medium
20	Brazos	1980	Arkansas	Medium
21	Brazos	1980	Texas	Medium
22	Brazos	1980	Louisiana	Medium
23	Brazos	1980	Mississippi	Medium
24	Nova 76	1979	Arkansas	Medium
25	Nova 76	1979	Texas	Medium
26	Nova 76	1980	Arkansas	Medium
27	Nova 76	1980	Texas	Medium
28	Nova 76	1980	Louisiana	Medium
29	Pecose	1979	Arkansas	Medium
30	Pecose	1979	Texas	Medium
31	Pecose	1980	Arkansas	Medium
32	Pecose	1980	Texas	Medium
33	Pecose	1980	Mississippi	Medium
34	Vista	1979	Arkansas	Medium
35	Vista	1979	Texas	Medium
36	Vista	1980	Texas	Medium
37	Vista	1980	Louisiana	Medium
38	Vista	1980	Mississippi	Medium
39	M101	1979	Arkansas	Medium
40	M101	1980	Arkansas	Medium
41	M9	1979	Arkansas	Medium
42	M9	1980	Arkansas	Medium
43	La 110	1979	Arkansas	Medium
44	La 110	1979	Texas	Medium
45	La 110	1980	Arkansas	Medium
46	La 110	1980	Texas	Medium
47	Girona	1979	Texas	Medium
49	RU7803097	1979	Texas	Medium
50	RU7803097	1980	Texas	Medium
51	Nortai	1979	Arkansas	Short
52	Nortai	1979	Texas	Short
53	Nortai	1980	Arkansas	Short

(Continued)

Table 1.—(Continued)

Sample number	Variety	Year	State	Grain type
54	Nortai	1980	Texas	Short
55	Nortai	1980	Mississippi	Short
56	Mochi Gomi	1979	Texas	Short
59	Starbonnet	1979	Arkansas	Long
60	Starbonnet	1979	Texas	Long
61	Starbonnet	1980	Arkansas	Long
62	Starbonnet	1980	Texas	Long
63	Starbonnet	1980	Louisiana	Long
64	Starbonnet	1980	Mississippi	Long
65	Bonnet 73	1979	Arkansas	Long
66	Bonnet 73	1979	Texas	Long
67	Bonnet 73	1980	Arkansas	Long
68	Bonnet 73	1980	Texas	Long
69	Dawn	1979	Arkansas	Long
70	Dawn	1980	Arkansas	Long
71	Dawn	1980	Texas	Long
72	Dawn	1980	Louisiana	Long
73	Dawn	1980	Mississippi	Long
74	Lebonnet	1979	Arkansas	Long
75	Lebonnet	1979	Texas	Long
76	Lebonnet	1980	Arkansas	Long
77	Lebonnet	1980	Texas	Long
78	Lebonnet	1980	Louisiana	Long
79	Lebonnet	1980	Mississippi	Long
80	Labelle	1979	Arkansas	Long
81	Labelle	1979	Texas	Long
82	Labelle	1980	Arkansas	Long
83	Labelle	1980	Texas	Long
84	Labelle	1980	Louisiana	Long
85	Labelle	1980	Mississippi	Long
86	Newrex	1979	Arkansas	Long
87	Newrex	1979	Texas	Long
88	Newrex	1980	Arkansas	Long
89	Newrex	1980	Texas	Long
90	Newrex	1980	Louisiana	Long
91	Newrex	1980	Mississippi	Long
92	Bellemont	1979	Arkansas	Long
93	Bellemont	1979	Texas	Long
94	Bellemont	1980	Arkansas	Long
95	Bellemont	1980	Texas	Long
96	Bellemont	1980	Mississippi	Long
97	L201	1980	Arkansas	Long
98	L201	1980	Texas	Long
99	Blue Belle	1979	Texas	Long
100	Blue Belle	1980	Texas	Long
101	RU7801077	1979	Arkansas	Long
102	RU7801077	1979	Texas	Long
103	RU7801077	1980	Arkansas	Long
104	RU7801077	1980	Texas	Long
105	RU7801077	1980	Mississippi	Long

(Continued)

Table 1.—(Continued)

Sample number	Variety	Year	State	Grain type
106	RU7901045	1979	Texas	Long
107	RU7901045	1979	Texas	Long
108	RU7901045	1980	Arkansas	Long
109	RU7901045	1980	Texas	Long
110	RU7603015	1979	Arkansas	Long
111	RU7603015	1980	Arkansas	Long
112	RU7603015	1980	Texas	Long
113	RU8002026	1980	Arkansas	Long
114	RU8002026	1980	Texas	Long
115	RU8002026	1980	Louisiana	Long
116	RU8002026	1980	Mississippi	Long

Table 2.—Rice samples by grain type used in developing and validating the predictive models

Grain type	No. samples
Short	6
Medium	49
Long	58
Total	113

The moisture of each rough rice sample was determined, using a Motomco Moisture Meter, Model 919. The weight of each rough rice sample received and the corresponding moisture content were recorded.

A 250-gram quantity of each rough rice sample was hulled using the McGill Sheller according to the U. S. Department of Agriculture Handbook (*39*). Following shelling, the brown rice weight was noted for each sample.

Prior to milling, using a McGill No. 2 mill, each brown rice sample was divided into two aliquots using a Seedburo Equipment Company Partition Divider. Each aliquot was milled for 60 seconds with weight on the leverage arm. Following milling of both aliquots, each sample was recombined and the weight of the milled sample was determined.

All samples were graded using the rice sizing device, collecting only the head rice. The weight of the head rice recovered was then determined for each sample. Throughout the preparation and processing steps, samples were stored in sealed, glass containers awaiting the next step. A flow diagram illustrating the processing steps is shown in Figure 2.

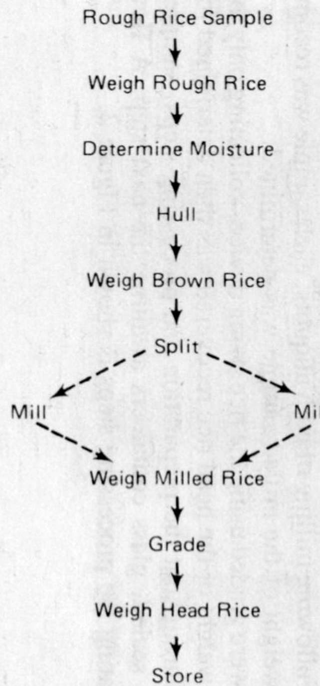

Fig. 1.—Sample preparation flow diagram.

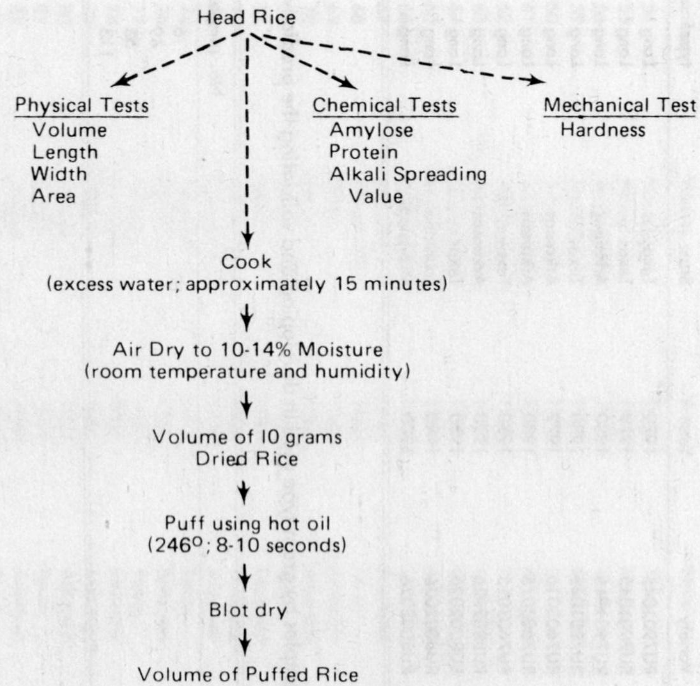

Fig. 2.—Experimental procedure flow diagram.

Physical and Mechanical Properties

Hardness.—Ten kernels of milled rice were selected at random from each sample. Only mature, undamaged, whole kernels were used in the hardness tests.

Each grain was tested by direct compression using an Instron Universal Testing Machine. The hardness value for each sample was determined by averaging the yield point loads for each kernel within that sample.

Volume.—The volume of the individual rice samples was determined from kerosene displacement. Exactly 2 milliliters (ml) of kerosene were placed in the small 10-ml graduated cylinder. Rice kernels selected at random from each sample were inspected to ensure that only undamaged, fully mature kernels would be used. The kernels were added one at a time to the kerosene, noting the number that were required to cause a 0.3-ml volume displacement. Kerosene was used because of the negligible absorption by rice of kerosene. The average volume for each sample was determined by dividing the number of kernels added by the 0.3-ml displacement.

Length, Width, Area.—A new procedure using a computerized interactive image analyzer was developed for determination of length, width, and area. The values resulting from this new procedure were compared with those obtained through use of conventional microscopic procedures for verification.

The principles of operation were discussed by Swenson and Attle (*36*). A review of typical applications of image analysis was given by Attle, Oney, and Swenson (*2*), and the interactive nature of using image analysis was reported by Terrell (*38*).

For this study, an equation was developed by Dr. J. I. Wadsworth, USDA, New Orleans, Louisiana, which fitted the major and minor axes of the rice kernels to the perimeter data by asssuming the rice kernel to be ellipsoid in shape. Fifty kernels of each sample were placed under the camera for analysis. The samples were scanned and analyzed. The output for each sample consisted of the sample identification number, the total number of kernels analyzed, the individual kernel parameter values (perimeter, area, length, width, and length-width ratio), the parameter mean, the maximum and minimum values, the standard deviation, and the parameter frequency histogram. The parameters measured were perimeter, area, length, width, and length-width ratio.

Chemical Properties

Amylose.—Each of the 113 rice samples was analyzed for amylose utilizing the simplified procedure of Juliano (*14*). The basis of this test is the iodine-amylose complex, which can be quantitatively measured at 620 nanometers (nm).

Protein.—The protein content of each of the ground samples was determined following the Technicon Industrial Method Number 325-74W (*37*) on a Technicon Auto Analyzer II system.

Alkali Spreading Value.—The alkali spreading values for each of the 113 head rice samples were determined following the procedure outlined by Little et al. (*21*).

Cooking, Drying, and Puffing

The gelatinization of rice prior to puffing was accomplished by cooking the rice samples in excess water, i.e. eight volumes of water per unit of rice, or 400 ml of water for 50 gm of rice. Each sample was added to boiling water and cooked until fully gelatinized, i.e. until no kernels showed white centers when pressed between glass plates. Typically, it took 12 to 15 minutes for each sample to become fully cooked.

Following cooking, each sample was spread uniformly over a 24-inch by 24-inch screen wire tray. The trays were placed in the drying rack. Each sample was air dried to a moisture content of 10 percent to 14 percent. Upon reaching the desired moisture level, each sample was placed into a glass container and sealed, allowing equilibration of within and among grain moisture levels.

The equilibrated samples were then puffed in vegetable oil maintained at 246°C. Prior to puffing, the moisture and the bulk volume of 10 gm of the cooked and dried rice was determined and recorded using a 100-ml graduated cylinder. The rice sample was then transferred to the wire basket and immersed in the hot oil for 8 to 10 seconds, with care taken not to scorch the rice. The puffed rice was patted dry to remove excess oil, and the bulk volume of the puffed rice was determined using either a 100-ml or 250-ml graduated cylinder. The degree of puffing was determined using the following: $X = F/I$, where X is the volumetric increase, or degree of puffing, F is the final volume, or the volume of the puffed rice, and I is the initial volume, or the volume of the cooked, dried rice.

Computer Analysis

The various data reduction and statistical analysis procedures used were performed on an IBM 370/3033 computer system. The programs for analysis of variance, correlation analysis and multiple regression were part of the Statistical Analysis System software package from the SAS Institute, Inc., Cary, North Carolina. Any FORTRAN programs were either run under the Waterloo WATFIV compiler or the IBM-supplied FORTRAN-G compiler.

Results and Discussion

Under laboratory conditions designed to simulate as closely as possible a typical industrial rice processing environment, 113 samples of several varieties and types of rice were milled and the resulting head rice analyzed for selected physicochemical properties. From these analyses the quantitative interrelationships of several of these properties were established and correlated to thermal and mechanical behavioral characteristics of the cooked and dried rice samples. Empirical models were developed from the rice quality characteristics for predicting the hardness, or resistance to deformation, of milled rice, and the puffing of gelatinized dried rice.

Preparation of Samples

Rough Rice Weight and Moisture.—The moisture content to which the rough rice is dried may exert an effect on the processing behavior of rice by influencing the internal structure of the kernel or perhaps the crystalline or micellar arrangement of starch and/or protein. Because of its ability to have such effects, it was considered essential that rough rice moisture be measured and included in the model development phase of this work.

Following the procedures given in the USDA Inspection Handbook (*39*), the moisture content of the rough rice was determined for each sample. Correlation data for rough rice moisture levels are summarized in Table 3.

The highly significant negative correlation between rough rice moisture content and hardness supports the earlier reported findings of Zoerb and Hall (*51*) and of Pomeranz and Meloan (*29*).

Table 3.—Correlation of rough rice moisture level with other physicochemical properties of the rice kernel

Physicochemical property	Rough rice moisture level (HOHR)
Hardness (LOAD)	$r = -0.31^{**}$
Brown rice yield (BRNYLD)	$r = +0.56^{**}$
Length-width ratio (LWRATIO)	$r = -0.30^{**}$
Alkali spreading value (KOH)	$r = +0.24^{*}$

**Highly significant ($P \leq .01$)
*Significant ($.01 < P \leq .05$)

Milling Yields

Although the milling yield parameters may not be directly related to the processing behavior of milled rice, it is reasonable to expect that some of those factors affecting hardness, e.g. resistance to breakage, could also effect the degree to which cooked, milled rice might be expected to expand.

Statistical analysis of head rice weights indicated that the yield from Mississippi (location 4) was significantly lower than those from Texas and Arkansas, but was only slightly lower than the yield from Louisiana. These data are shown in Table 4. Additionally, long-grain rice (type 3) varieties were shown to give significantly lower head rice weight yields than either short- (type 1) or medium- (type 2) grain varieties. This is shown in Table 5. Statistical analysis of percent head rice yields shows the same results, i.e., the yield from Mississippi was significantly below those from the other three states, and head rice yields of long-grain varieties were significantly less than those for either short- or medium-grain varieties.

A summary of the correlation coefficients for percentage yield of head rice, HDYLD, with other selected physicochemical parameters of milled rice is shown in Table 6.

Several factors seem to be important in affecting the yield of head rice. Since milling involves the abrading of kernel against kernel, it is intuitative that the longer, thinner kernels would tend to break more easily than the shorter, fatter kernels. Thus, it is consistent that milling yields of long grain varieties could be lower than those of short- or medium-grain varieties. Perhaps there were significantly different environmental factors in Mississippi that resulted in lowered yields for all grain types.

Table 4.—Mean separation by location of head rice weight

Grouping		Mean[1]	N	Location
	A	140.438636	44	2 (Texas)
	A	139.555814	43	1 (Arkansas)
B	A	134.750000	12	3 (Louisiana)
B		116.671429	14	4 (Mississippi)

[1] Means in the same letter grouping are not significantly different at $P \leqslant .05$ using Duncan's Multiple Range test.

Table 5.—Mean separation of head rice weight yields by grain type

Grouping	Mean[1]	N	Grain type
A	155.650000	6	1 (Short grain)
A	145.273469	49	2 (Medium grain)
B	127.212069	58	3 (Long grain)

[1] Means in the same letter grouping are not significantly different at $P \leqslant .05$ using Duncan's Multiple Range test.

Table 6.—Correlation of percentage yield of head rice with other selected physicochemical properties of the rice kernel

Physicochemical property	Percent yield of head rice (HDYLD)
Amylose content (AMYLOSE)	$r = -0.48$**
Alkali spreading value (KOH)	$r = +0.30$**
Length-width ratio (LWRATIO)	$r = -0.38$**
Hardness (LOAD)	$r = +0.22$*

**Highly significant ($P \leqslant .01$)
*Significant ($.01 < P \leqslant .05$)

Physical and Mechanical Properties

Hardness.—Because puffing alters the shape and changes the dimensions of the rice kernel, it is not unreasonable to suspect that kernel hardness might influence the degree to which a kernel will expand. Moreover, those physicochemical properties responsible for kernel hardness may act to either retard or potentiate the puffing process.

Statistical analysis of hardness data by location showed that rice varieties grown in Louisiana (location 3) had significantly higher yield points than varieties grown in the other three states. This is summarized in Table 7. It also was observed that short-grain varieties had lower yield points than either medium- or long-grain varieties, as shown in Table 8.

The correlation analysis of hardness with the other physicochemical parameters of this study indicated a limited degree of associativity of hardness with these parameters. The results of that correlation analysis are given in Table 9.

The expected correlation with protein did not materialize ($r = 0.18$), differing with the earlier work reported by Juliano (*13*). The lack of a significant correlation of hardness with amylose ($r = -0.17$) is consistent

Table 7.—Mean separation of milled rice kernel hardness by location

Grouping	Mean[1]	N	Location
A	23.383333	12	3
B	20.939535	43	1
B	20.763636	44	2
B	19.785714	14	4

[1] Means in the same letter grouping are not significantly different at $P \leq .05$ using Duncan's Multiple Range test.

Table 8.—Mean separation of milled rice kernel hardness by grain type

Grouping	Mean[1]	N	Type
A	21.481633	49	2
A	20.855172	58	3
B	18.233333	6	1

[1] Means in the same letter grouping are not significantly different at $P \leq .05$ using Duncan's Multiple Range test.

Table 9.—Correlation of milled rice kernel hardness with other selected physicochemical properties of the rice kernel

Physicochemical property	Hardness (LOAD)
Rough rice moisture (HOHR)	$r = -0.31$**
% yield of head rice (HDYLD)	$r = +0.22$*
Area-volume ratio (AVRATIO)	$r = +0.38$**

** Highly significant ($P \leq .01$)
* Significant ($.01 < P \leq .05$)

with the findings of Kongeree and Juliano (*20*). The physicochemical parameter giving the highest correlation with hardness was area-to-volume ratio ($r = 0.39$). This correlation was highly significant and heretofore has not been reported in the literature. As to be expected from review of the literature, rough rice moisture content correlation to hardness was found to be highly significant (*51*). And as expected, percent yield of head rice was also found to be significantly correlated to hardness.

It is felt that the lack of significant correlation between hardness and alkali spreading value or between hardness and expansion is important. Since alkali spreading value has been related to kernel porosity (*20*), it might be assumed that compact, less porous kernels, showing high alkali spreading values, would be ''harder'' than those kernels with higher degrees of porosity and, hence, lower alkali spreading values. But, it would appear that this supposition is incorrect or at least not borne out by these data. Hardness and kernel porosity are not highly correlated parameters among the rice varieties in this study, nor is hardness highly correlated to expansion.

To gain more information concerning hardness and its interrelationships with other physicochemical properties of rice, graphs plotting hardness against each of several selected physicochemical parameters were generated. These graphs showed a general scattering effect with no clear mathematical relationship evident between hardness and any other parameter.

Regression analysis was then used to find the best fit for a linear relationship describing hardness in terms of other physicochemical parameters selected for analysis. The goals of regression analysis are two-fold. First, the regression model should account for as much of the variation in the dependent variable, hardness, as possible; i.e., the value of R^2, the coefficient of multiple determination which ranges from 0 to 1, should be as high as possible. Second, the regression model should, for reasons of economy, contain as few independent variables as possible.

In modeling, it is very important to have some means by which the generated model can be validated. Given large enough sample sizes (or numbers of observations), the best method for validation is to use a hold-out sample consisting of some percentage of the original numbers of observations. For this investigation, 30 of the original observations were chosen at random, by drawing sample numbers out of a hat, to be used as the hold-out sample, leaving 83 observations for use in model development work.

After development of a few significant regression equations, each equation was tested or validated using the hold-out samples. The dependent variable was predicted from the individual observations in the hold-out sample using the respective models. The variation between observed and predicted values was analysed for each model, and that model showing the best overall performance was selected as the regression model. The criteria for best overall performance included (1) the highest number of predicted values with ± 10 percent of the observed, and (2) the smallest range of percent variation between predicted and observed values.

The regression procedure calculates an F* statistic for each of the independent variables which indicates how much of the variation in the dependent variable is explained by each particular independent variable. The F* statistic is the value MSR divided by MSE where MSR is regression mean square and MSE is error or residual mean square.

$$MSR = \frac{SSR}{1} = \sum (\hat{Y}i - \bar{Y})^2$$

where $\hat{Y}_i$ is the predicted value of the independent variable and $\bar{Y}$ is the sample mean. Regression mean square is then the sum of the deviations of the fitted regression values around the sample mean, and represents that portion of the total variation removed or taken out by regression.

$$MSE = \frac{SSE}{df_E} = \frac{\sum (Yi\text{-}\hat{Y}i)^2}{df_E}$$

where SSE is the error or residual sum of squares and df_E is the appropriate degrees of freedom. This is the variation in the data, or the difference between observed and predicted values.

The objective of this data treatment was to determine which combinations of the independent variables gave the highest R^2 values. This was done using the SAS RSQUARE procedure. RSQUARE calculates the R^2 values for all possible combinations of the independent variables. The results of the regression analysis of hardness are summarized here. The two-variable model having the highest R^2 was found to be LOAD = 22.5 − 1.16*HOHR + 17.25*AVRATIO with the $R^2 = 0.23$. The three-variable model having the highest R^2 was found to be LOAD = 22.25 − 1.88*HOHR + 0.07*HDYLD + 16.48*AVRATIO with $R^2 = 0.30$. The four-variable model having the highest R^2 was found to be LOAD = 18.5 − 2.03*HOHR + 0.66*PROTEIN + 0.08*HDYLD + 15.3*AVRATIO with $R^2 = 0.35$. The marginal increase in R^2 by adding additional variables beyond four in this particular situation was decided to be too small to warrant consideration.

The next step to ensure the "goodness" of these models was to plot the residuals versus the predicted values. Plots of the residuals for each of the three above mentioned equations indicate a total random pattern to the residuals, which is the desired result since the error term, ϵi, in the generalized regression equation

$$Y_i = \beta_0 + \beta_1 X_i + \epsilon_i$$

is assumed to be random with normal distribution.

Prior to validating the models with the hold-out sample the models must be checked for significance, and the coefficients (the β's) must be checked to make sure they are valid. The model significance can be determined by making sure that the significance probability, PR > F on the output, for the individual F statistics is small. It can be seen from Table 10 that all three models are significant, with the significance probability equal to 0.0001 in all cases. It is important also to note that although the R^2 values are relatively low, explaining only 23 percent to 35 percent of the total variation in hardness, the error mean squares are quite low with regard to the regression mean squares.

Table 10.—Significance evaluation of hardness regression models

Model	F value	Significance probability (Pr > F)	Coefficient of multiple determination (R^2)	Regression mean square (MSR)	Error mean square (MSE)	Degrees of freedom for MSE
(1) HOHR AVRATIO	11.88	0.0001	0.23	73.13	6.16	80
(2) HOHR HDYLD AVRATIO	11.15	0.0001	0.30	63.34	5.68	79
(3) HOHR PROTEIN HDYLD AVRATIO	10.36	0.0001	0.35	55.41	5.35	78

To determine if any of the coefficients are significantly different from zero, the statistics on the parameter estimates must be evaluated. These statistics are summarized in Tables 11, 12, and 13. For all three models the coefficients are significant at $P \leqslant = 0.5$.

Having established the significance of the overall model and the individual coefficients, each model was next validated using the hold-out sample. Validation consisted of computing the predicted hardness value for each rice sample in the hold-out group, and comparing the predicted result with the actual observed result. The results for each model are given in Tables 14, 15, and 16. Using the previously established criteria for overall performance (that of having the highest number of predicted values within $\pm$ 10 percent of the observed and having the smallest range in percent variation), Table 17 was constructed for the three regression models for hardness. From this table, it can be seen that model 2 best fits the criteria for the best model generated.

Table 11.—Parameter estimates for hardness, Model 1

Parameter	Estimate	T* statistic	Probability of T
INTERCEPT	22.5	3.03	0.0033
HOHR	−1.61	−2.89	0.0049
AVRATIO	17.25	3.69	0.0004

Table 12.—Parameter estimates for hardness, Model 2

Parameter	Estimate	T* statistic	Probability of T
INTERCEPT	22.25	3.12	0.0026
HOHR	−1.88	−3.46	0.0009
HDYLD	0.07	2.77	0.0069
AVRATIO	16.48	3.66	0.0005

Table 13.—Parameter estimates for hardness, Model 3

Parameter	Estimate	T* statistic	Probability of T
INTERCEPT	18.5	2.61	0.0109
HOHR	−2.03	−3.83	0.0003
PROTEIN	0.66	2.43	0.0173
HDYLD	0.08	3.22	0.0019
AVRATIO	15.37	3.50	0.0008

Using the three-variable model, model 2, the SAS procedure SYSREG was run to generate the standardized coefficients for the model. This was necessary to determine the quantitative effect of each variable upon the model. Prior to standardization, the coefficients are in different units, so no direct comparison concerning magnitude of the respective independent variables could be made. By specifying the STB option with the SAS procedure SYSREG, each coefficient is multiplied by the standard deviation of its associated variable and divided by the standard deviation of the dependent variable. The result is a set of modified parameters or coefficients which allow direct comparison of the effect of each independent variable. The regression model for hardness using standardized coefficients is: LOAD = 0.35*AVRATIO + 0.27*HDYLD − 0.33*HOHR.

Although the model developed for describing kernel hardness only accounts for approximately 30 percent of the variation in hardness, it does appear to be significant due to its very low variance, and the accuracy with which hardness values were predicted in the validation with the hold-out samples.

Table 14.—Validation results of hardness, Model 1

Sample number	Observed load (pounds)	Predicted load (pounds)	Difference	Percent difference
11	22.0	22.44	− 0.44	− 1.99
13	23.0	20.13	2.87	12.49
14	22.5	20.87	1.63	7.26
22	32.1	21.32	10.78	33.60
23	21.2	21.34	− 0.14	− 0.66
24	24.4	20.46	3.94	16.14
27	21.2	21.22	− 0.02	− 0.08
30	20.1	20.82	− 0.72	− 3.60
35	21.5	19.31	2.19	10.19
42	23.9	21.89	2.01	8.41
43	20.0	20.54	− 0.54	− 2.70
49	20.0	17.95	2.05	10.27
52	17.2	20.47	− 3.27	−19.04
53	17.9	20.23	− 2.33	−13.02
55	17.3	18.20	− 0.90	− 5.20
56	18.8	17.93	0.87	4.64
60	16.1	21.32	− 5.22	−32.44
62	22.9	20.81	2.09	9.13
67	16.4	18.36	− 1.96	−11.96
71	22.9	20.33	2.57	11.22
72	20.9	21.48	− 0.58	− 2.79
82	21.4	20.59	0.81	3.80
87	16.5	21.63	− 5.13	−31.08
89	18.9	22.71	− 3.81	−20.15
93	28.8	25.60	3.20	11.11
96	24.8	21.06	3.74	15.06
100	20.3	21.73	− 1.43	− 7.03
102	21.4	21.10	0.30	1.40
105	18.2	19.83	− 1.63	− 8.96
110	23.2	21.56	1.64	7.06

Table 15.—Validation results for hardness, Model 2

Sample number	Observed hardness	Predicted hardness	Difference	Percent difference
11	22.0	23.37	− 1.37	− 6.21
13	23.0	20.83	2.17	9.45
14	22.5	21.52	0.98	4.36
22	32.1	21.73	10.37	32.32
23	21.2	20.97	0.23	1.08
24	24.4	20.65	3.75	15.36
27	21.2	19.96	1.24	5.84
30	20.1	21.32	− 1.22	− 6.07
35	21.5	20.54	0.96	4.45
42	23.9	22.35	1.55	6.48
43	20.0	18.78	1.22	6.10
49	20.0	18.00	2.00	10.01
52	17.2	21.24	− 4.04	−23.50
53	17.9	20.26	− 2.36	−13.16
55	17.3	18.80	− 1.50	− 8.70
56	18.8	18.19	0.61	3.26
60	16.1	21.24	− 5.14	−31.95
62	22.9	20.73	2.17	9.46
67	16.4	17.66	− 1.26	− 7.67
71	22.9	20.60	2.30	10.06
72	20.9	21.58	− 0.68	− 3.26
82	21.4	20.60	0.80	3.75
87	16.5	21.71	− 5.21	−31.59
89	18.9	23.20	− 4.30	−22.76
93	28.8	26.29	2.51	8.73
96	24.8	20.68	4.12	16.59
100	20.3	21.85	− 1.55	− 7.63
102	21.4	21.63	− 0.23	− 1.08
105	18.2	19.25	− 1.05	− 5.78
110	23.2	22.22	0.98	4.22

Table 16.—Validation results for hardness, Model 3

Sample number	Observed hardness	Predicted hardness	Difference	Percent difference
11	22.0	23.01	− 1.01	− 4.59
13	23.0	19.90	3.10	13.48
14	22.5	21.87	0.63	2.78
22	32.1	20.64	11.46	35.72
23	21.2	21.66	− 0.46	− 2.16
24	24.4	19.76	4.64	19.04
27	21.2	19.63	1.57	7.41
30	20.1	21.44	− 1.34	− 6.64
35	21.5	21.70	− 0.20	− 0.93
42	23.9	22.88	1.02	4.25
43	20.0	18.45	1.55	7.77
49	20.0	18.17	1.83	9.15
52	17.2	20.72	− 3.52	−20.44
53	17.9	19.65	− 1.75	− 9.80
55	17.3	17.53	− 0.23	− 1.33
56	18.8	17.59	1.21	6.43
60	16.1	21.04	− 4.94	−30.67
62	22.9	20.41	2.49	10.85
67	16.4	17.51	− 1.11	− 6.75
71	22.9	19.67	3.23	14.13
72	20.9	20.63	0.27	1.31
82	21.4	20.54	0.86	4.02
87	16.5	23.36	− 6.86	−41.57
89	18.9	23.51	− 4.61	−24.41
93	28.8	27.22	1.58	5.48
96	24.8	21.60	3.20	12.91
100	20.3	22.00	− 1.70	− 8.40
102	21.4	22.45	− 1.05	− 4.90
105	18.2	19.48	− 1.28	− 7.04
110	23.2	22.12	1.08	4.66

Table 17.—Comparison of validation results for the three hardness regression models

Model	Percent of predicted within ± 10% of observed	Range of percent deviation from observed (%)
1	53.3	−32.4 to 33.6
2	66.7	−31.9 to 32.3
3	66.7	−41.6 to 35.7

Volume.—The volume of the rice kernel, either expressed in terms of an area-volume ratio, or simply as volume, is involved in the puffing of rice. The "amount of kernel" that surrounds any moisture in the center of the grain affects at least two processing parameters, (1) the amount of thermal energy required to penetrate the kernel to flash any moisture in the center of the grain, and (2) the distance moisture within the kernel must travel to escape is directly related to volume. Moreover, only limited data can be found in the literature regarding the volume measurements of domestic rice varieties.

The volume of the milled rice samples was determined by measuring kerosene displacement. Statistical analysis of the rice volume data indicated significant variation by location, as seen in Table 18, and by type, shown in Table 19. The difference in kernel volume by location is probably not as significant as the difference based on type. Close analysis of Table 18 shows rice varieties from Arkansas and Louisiana have the different volumes, and those of Mississippi and Texas have volumes intermediate to those from either Arkansas or Louisiana. It should also be pointed out that these volume measurements are averages for short-, medium-, and long-grain types.

It can be seen from Table 19 that a discernable difference in volume exists between medium-grain types and long-grain types. Short-grain varieties are shown to have volumes similar to those of both medium- and long-grain varieties.

Table 18.—Mean separation of milled rice kernel volume by location

Grouping		Mean[1]	N	Location
	A	13.800000	43	1
	A			
B	A	13.407143	14	4
B				
B		13.225000	44	2
B				
B		13.141667	12	3

[1] Means in the same letter grouping are not significantly different at $P \leq .05$ using Duncan's Multiple Range test.

Table 19.—Mean separation of milled rice kernel volume by grain type

Grouping		Mean[1]	N	Type
	A	13.826531	49	2
	A			
B	A	13.600000	6	1
B				
B		13.131034	58	3

[1] Means in the same letter grouping are not significantly different at $P \leq .05$ using Duncan's Multiple Range test.

Length, Width, Area.—In the consideration of the possible response of rice to different processing environments, the physical parameters of length, width, and area cannot be overlooked. The regression model for hardness utilizes as one of the independent variables the area-volume ratio of the kernel. The U. S. Department of Agriculture relies upon the ratio of length to width for classification of rice into three different grain types (*47*), as shown in Table 20.

The conventional method for measuring length and width of rice kernels utilizes either a projecting microscope, or a conventional microscope with a measurement grid in the substage. Both of these techniques were used to determine the length and width of sample number 1, MARS, a medium-grain commercial variety of rice from the 1979 Arkansas crop. The results of these measurements are shown in Table 21. It should be noted that 10 kernels were used for each analysis and it took approximately 10 minutes for each analysis.

Table 22 contains a summary of the measurements of length, width, and area for 50 kernels of rice from the same sample, as determined using the

Table 20.—Rice grain classification based on length-to-width ratio

Grain type	Length-width ratio range
Short	1.9:1 and less
Medium	2.0:1 to 2.9:1
Long	3.0:1 and greater

Table 21.—Comparison of two microscopic methods for determination of length and width of sample number 1

	Measurement (mm)			
	Wilder Vari-beam Projection Microscope		Gaertner Microscope	
Observation	Length	Width	Length	Width
1	6.1	2.5	5.84	2.67
2	6.0	2.5	6.35	2.67
3	6.0	2.6	6.48	2.67
4	5.7	2.3	6.22	2.54
5	6.3	2.6	6.35	2.67
6	6.4	2.5	6.35	2.54
7	5.8	2.6	6.10	2.54
8	6.1	2.5	6.10	2.67
9	6.0	2.3	6.22	2.67
10	6.0	2.7	6.22	2.54
Mean	6.0	2.5	6.22	2.62
Std. dev.	0.21	0.13	0.18	0.07
C.V.	3.5%	5.2%	2.9%	2.7%
Time for analysis	10 mins.		10 mins.	

Table 22.—Length, width, and area determination of sample number 1 using image analysis

Parameter	n	Mean	Standard deviation	Coefficient of variation
Length (mm)	50	6.28	0.30	4.8%
Width (mm)	50	2.67	0.08	3.0%
Area (mm^2)	50	13.17	0.88	6.68%

Time for analysis: 3 minutes.

image analyzer. As can be seen, using the image analyzer allows for sampling a larger number of kernels per measurement and, due to the computer system used, reports on statistical measurements are automatically generated. Also, a greater number of parameters can be measured simultaneously, e.g. area, perimeter, and length-to-width ratio in addition to length and width, in much less time.

Comparison of the data in Tables 21 and 22 indicates quite good agreement among the three methods. Moreover, a preliminary study with the image analyzer showed that grain orientation in the scanning area was not important, thus allowing for a more rapid procedure since the kernels can be more or less just thrown under the camera. The only restraint is that kernels may not be touching one another.

The image analysis technique solves still another problem associated with physical measurements of rice. As previously mentioned, the measurement of surface area is tedious at best due to the highly irregular shape of the rice kernel. Methods presently available merely approximate the surface area. The area measurement obtained by image analysis is properly considered to be a cross-sectional area taken along the major axis parallel to the minor axis assuming an elliptical two-dimensional shape for the rice kernel. However, this value is easy to obtain, easy to reproduce, and is currently under consideration by the U. S. Department of Agriculture for use as an approximation of the surface area of the rice kernel.

Mean separation of the length by type of grain showed that there were significant differences in length based on grain type, as shown in Table 23.

Length alone may not be very meaningful in studying the processing characteristics of rice, but when considered in conjunction with width, it provides meaningful descriptive data concerning the physical characteristics of the particular rice being studied. Statistical analysis by grain type showed no significant difference in the widths of short- and medium-grain varieties. The long-grain varieties were shown to be thinner than either the short- or medium-grain varieties (Table 24).

The combination of the parameters length and width gives the length-to-width ratio. This, as previously mentioned, is the primary basis for the categorization of rice into three grain types, short, medium, and long. As would be expected, mean separation of length-to-width ratio by grain type

Table 23.—Mean separation of milled rice length by grain type

Grouping	Mean[1]	N	Type
A	6.813793	58	3
B	5.860000	49	2
C	5.353333	6	1

[1] Means in the same letter grouping are not significantly different at $P \leq .05$ using Duncan's Multiple Range test.

Table 24.—Mean separation of milled rice width by grain type

Grouping	Mean[1]	N	Type
A	2.731667	6	1
A	2.671429	49	2
B	2.170862	58	3

[1]Means in the same letter grouping are not significantly different at $P \leqslant .05$ using Duncan's Multiple Range test.

gave statistically distinct values for each grain type as shown in Table 25. The sample having the lowest length-to-width ratio was the Italian variety Mochi Gomi from the 1979 Texas crop, while the sample with the highest ratio was L201 from the 1980 Texas crop.

Correlation analysis showed length-to-width ratio was significantly correlated to several other physicochemical parameters of the rice samples in this study. These correlations are given in Table 26. Of interest is the high positive correlation to both amylose and alkali spreading value and the positive correlation to expansion or puffing. Since length-to-width ratio is a direct measure of grain type, the above suggests amylose, alkali spreading, and expansion would each have the lowest values for short-grain varieties, increase in value slightly for medium-grain varieties, and have the highest values for long-grain varieties. This trend is reflected in the results of this study. Perhaps a more useful observation is that with the samples used in this study it appears that length-to-width ratio accounts for approximately 9 percent of the observed variation in rough rice moisture levels, indicating a possible effect in the drying of rice.

Table 25.—Mean separation of length-width ratio values of milled rice by grain type

Grouping	Mean[1]	N	Type
A	3.139782	58	3
B	2.196519	49	2
C	1.959010	6	1

[1]Means in the same letter grouping are not significantly different at $P \leqslant .05$ using Duncan's Multiple Range test.

Table 26.—Correlation of milled rice length-width ratio with other selected physicochemical properties of the rice kernel

Physicochemical property	Length-width ratio (LWRATIO)
Rough rice moisture (HOHR)	$r = -0.30^{**}$
Amylose (AMYLOSE)	$r = 0.78^{**}$
Alkali spreading value (KOH)	$r = -0.92^{**}$
Expansion (EXP)	$r = 0.62^{**}$
Percent yield of head rice (HDYLD)	$r = -0.38^{**}$

**Highly significant ($P \leqslant .01$)

Chemical Properties

Amylose.—The importance of amylose content in determining quality characteristics of rice is mentioned in virtually all reports on rice quality or rice processing. The reports that rice samples with high amylose content expanded or puffed poorly in relation to those samples with lower amylose content certainly indicated amylose played a key role in the thermal processing of cooked rice. There is an anomaly in the literature wherein amylose has been positively correlated to increases in cooked volume of rice (*19*) and negatively correlated with increases in puffed volume of cooked rice (*1*, *16*, *28*). There has been no explanation for this apparent contradiction.

Thus, to further investigate the role of amylose in the puffing of cooked rice, all 113 samples were analyzed for this controversial property. Analysis of variance showed no significant differences in amylose content due to geographical location, but it was found that amylose content varied significantly among short-, medium-, and long-grain types, as shown in Table 27.

Correlation analysis of amylose with other selected physicochemical properties of the rice kernel indicated significant relationships to several other parameters. The results of the correlation analysis are summarized in Table 28. The high correlation between amylose and both grain type and length-width ratio would be expected if the amylose were found correlated to either one since both grain type and length-width ratio are synonymous. The relatively strong negative correlation between amylose and alkalai spreading value is consistent with general observations, i.e. long-grain varieties typically have high amylose contents and low alkali spreading values.

Table 27.—Mean separation of milled rice amylose content by grain type

Grouping	Mean[1]	N	Type
A	22.563793	58	3
B	14.644898	49	2
C	11.133333	6	1

[1] Means in the same letter grouping are not significantly different at P ≤ .05 using Duncan's Multiple Range test.

Table 28.—Correlation analysis of amylose content with other selected physicochemical properties of the rice kernel

Physicochemical property	Amylose content
Alkali spreading value (KOH)	r = −0.64**
Expansion (EXP)	r = +0.36**
Percent yield of head rice (KDYLD)	r = −0.48**
Length-width ratio (LWRATIO)	r = +0.78**

**Highly significant (P ≤ .01)

Two rather surprising relationships emerged from the correlation analysis of amylose. The negative correlation to head rice yield has not appeared previously in the literature. The positive, not negative, correlation to puffing of cooked rice differs from previously published results. Herein in a paradox of nature. If a breeder wished to produce a variety of rice for puffing, he would select varieties with high amylose content, but in so doing, the resulting yield would decrease due to the increased amylose. Fortunately the relationship is not that static in that from these correlation coefficients it would appear that amylose content can account for only 16 percent of the variation in expansion and for approximately the same percentage in the variation of head rice yield. There are certainly other factors influencing both expansion and yield, but amylose would appear to be important to both.

In associating amylose content with grain type, it should be noted that there are medium-grain varieties with high amylose content, e.g. samples 43 through 46, which are samples of the medium-grain variety L110, and samples 49 and 50, both medium-grain samples of the experimental variety RU7803097. It would be inappropriate to say all short- and medium-grain rice varieties have low amylose contents while long-grain rice varieties all have high amylose contents.

Protein.—The ability of protein to bind water is well recognized in the areas of biochemistry and food technology. The lack of any report in the literature correlating protein with the processing characteristics of rice, other than with hardness, is puzzling. Because of the possibility of protein interacting with internal moisture, it was decided to include protein as one of the selected properties to be measured in this study.

Statistical analysis showed that protein content varied geographically as well as by type. The data in Table 29 shows that the mean protein content for all samples from Louisiana was lower than for those from the other three states. Since it is common knowledge that protein content of rice can be affected by seasonal conditions and by time and amount of fertilization, this geographical difference may not be significant.

Separation of mean protein content by grain type (Table 30) showed a significant difference in levels between short-grain varieties and varieties of either medium- or long-grain types. The lower value for short-grain

Table 29.—Mean separation of milled rice protein content by location

Grouping	Mean[1]	N	Location
A	8.893023	43	1
A	8.857143	14	4
A	8.722727	44	2
B	7.766667	12	3

[1]Means in the same letter grouping are not significantly different at $P \leq .05$ using Duncan's Multiple Range test.

Table 30.—Mean separation of milled rice protein content by grain type

Grouping	Mean[1]	N	Type
A	8.767347	49	2
A	8.762069	58	3
B	7.600000	6	1

[1]Means in the same letter grouping are not significantly different at P ≤ .05 using Duncan's Multiple Range test.

varieties may partially explain the broad use of short-grain rice in preparing puffed rice products since protein is correlated negatively with puffing.

Correlation analysis of protein content with other selected physicochemical properties showed significant correlation only with expansion ($r = -0.25$ with $P = 0.0078$). The negative correlation, albeit small, tends to support the water binding importance of protein to puffing, as previously discussed.

Alkali Spreading Value.—The synonymous nature of alkali spreading value and gelatinization temperature has been well documented (*15*, *18*, *20*, *21*), but the correlation of most interest is that between alkali spreading value and rice kernel compactness (*20*), which in all probability also relates back to gelatinization temperature.

Separation of the mean alkali spreading values showed no differences attributable to geographic location, but as the data in Table 31 clearly shows, there are significant differences in the alkali spreading values for each of the three grain types.

The results of the correlation analysis of alkali spreading value with the other selected physicochemical properties studied are summarized in Table 32. These results might seem to differ significantly from some of those reported in the literature. There have been numerous reports correlating gelatinization temperature negatively to alkali spreading value (*15*, *18*, *20*, *21*). Additionally, there have been numerous reports stating there was no correlation between amylose and gelatinization temperature (*3*, *9*, *15*, *19*, *20*, *31*). However, Juliano et al. (*17*) reported that by removing two anomalous values there was a significant correlation with $r = +0.63$ between amylose and gelatinization temperature, while reporting elsewhere that there was no correlation (*15*, *19*, *20*, *31*).

Table 31.—Mean separation of alkali spreading value by grain type

Grouping	Mean[1]	N	Type
A	6.500000	6	1
B	5.775510	49	2
C	2.586207	58	3

[1]Means in the same letter grouping are not significantly different at P≤.05 using Duncan's Multiple Range test.

Table 32.—Correlation analysis of alkali spreading value with other selected physicochemical properties of the rice kernel

Physicochemical property	Alkali spreading value (KOH)
Rough rice moisture (HOHR)	r = +0.24*
Cooked rice moisture (HOHCK)	r = −0.24*
Amylose (AMYLOSE)	r = −0.64**
Expansion (EXP)	r = −0.65**
Percent yield head rice (HDYLD)	r = +0.30**
Length-width ratio (LWRATIO)	r = −0.92**

**Highly significant ($P \leq .01$)
*Significant ($.01 < P \leq .05$)

By accepting the negative correlation between alkali spreading value and gelatinization temperature, and applying the negative correlation between amylose content and alkali spreading, it may be concluded that amylose content would be positively correlated to gelatinization temperature, substantiating the earlier result of Juliano et al. (*17*). In any event, with the domestic samples used in this study, amylose is correlated to alkali spreading value.

The negative correlation with expansion is consistent with some of the results of Kongseree and Juliano (*20*) where they postulate that different gelatinization temperatures reflected the porosity of the kernel, presumably inversely, i.e., as the porosity decreases, the gelatinization temperature increases. Thus, due to the inverse relationships involved, kernel porosity and alkali spreading value are positively correlated, thus making expansion and kernel porosity negatively correlated. This conclusion is consistent with the generalized concept of puffing. That is, after the moisture within the kernel is flashed to steam there must be some resistance to the outward movement of the steam or there would be no puffing at all, rather just a collapse of the kernel structure.

Puffing

Following the analysis of the samples for those selected physicochemical parameters, each sample was fully gelatinized by cooking in excess water, air dried to an equilibrated moisture content between 10 percent and 14 percent, and puffed by taking measured volumes and placing them in vegetable oil at 246°C for 8 to 10 seconds. The volume expansion was determined by dividing the original volume of 10 grams of the cooked, dried rice into the puffed volume of the same sample.

Statistical analysis of expansion showed no differences in degree of expansion due to geographical origin, but there were significant differences based on grain type, as seen in Table 33. The long-grain varieties definitely showed a greater degree of expansion than that of either the medium- or short-grain varieties, by almost 20 percent. However, it should

Table 33.—Mean separation of expansion of cooked rice by grain type

Grouping	Mean[1]	N	Type
A	6.732759	58	3
B	5.836735	49	2
B	5.533333	6	1

[1] Means in the same letter grouping are not significantly different at P ≤ .05 using Duncan's Multiple Range test.

be noted that several medium-grain samples puffed as well as many of the long-grain samples. Specifically, Mars from Arkansas, 1979; Nato from Arkansas, 1980; Pecose from Mississippi, 1980; Vista from Texas in 1979 and 1980; RU8003072, an experimental variety from Mississippi in 1980, and RU7803097, an experimental variety from Texas in 1980, all expanded better than 6.4 times, which was the mean expansion for the long-grain varieties. Moreover, upon close examination of the data, it can be seen that all samples of Nato, Brazos, and Vista expanded very well, averaging expansions of 6.0 for Nato, 6.0 for Brazos, and 6.3 for Vista.

Correlation analysis prior to model development showed expansion to be correlated to several of the physicochemical parameters included in the study. The results of the correlation analysis are summarized in Table 34.

Most of the correlations have been discussed previously. The high negative correlation with alkali spreading value may indicate an increase in puffing with a decrease in rice kernel porosity. The relationship with amylose is unexplained, and is contrary to previously published reports, but it is evident that as amylose increased, the degree of puffing increased, with but four exceptions, those being samples 44, 45, 46, and 49.

Table 34.—Correlation analysis of cooked rice expansion with other selected physicochemical properties of the rice kernel

Physicochemical property	Expansion (EXP)
Cooked rice moisture (HOHCK)	r = +0.27*
Amylose (AMYLOSE)	r = +0.36**
Protein (PROTEIN)	r = −0.38**
Alkali spreading (KOH)	r = −0.65**
Length-width ratio (LWRATIO)	r = +0.62**

**Highly significant (P ≤ .01)
*Significant (.01 < P ≤ .05)

Expansion Model Development

The model to predict the degree of puffing of cooked rice was developed in the same manner as the one for predicting kernel hardness. The same sets of samples for generation and validation were used for the puffing or expansion model as were used for the hardness model. Likewise, the same criteria were used for model performance evaluation; the model giving (1) the highest number of predicted values within ± 10 percent of the observed, and (2) having the smallest range of variation will be the model selected for use.

As was done previously, prior to modeling, graphs were plotted to indicate any possible mathematical relationships that might exist between expansion and the other physicochemical properties investigated in this work. Inspection of these plots showed no discernible relationships for any of the parameters.

Regression analysis was used to find the best fit for a linear relationship describing expansion in terms of the other physicochemical parameters included in this study.

Two models were selected from the regression analysis, a two-variable model and a three-variable model.

The two-variable model having the highest R^2 was found to be EXP = 9.87 − 0.28 * % PROTEIN − 0.27 * KOH Value with $R^2 = 0.56$. The three-variable model having the highest R^2 was found to be EXP = 7.74 − 0.29 * % PROTEIN − 0.29 * KOH Value + 0.22 * % HOHR with $R^2 = 0.58$.

Having generated the models, it was necessary to evaluate the suitability of each. The first step was to check the plots of the residuals versus the predicted values. Observation of these plots showed the residuals for each model to be random which is as desired.

The second step in evaluating the models' suitability was the determination of the significance of the individual models. This was accomplished by checking the significance probability, PR > F, given for each regression output. These statistics are summarized in Table 35. As can be seen from Table 37, both models are significant, with the significance probability equal to 0.001 in all cases. Moreover, the R^2 values are quite high, explaining 56 percent and 58 percent of the variation in expansion.

The next step was the evaluation of the parameter estimates to determine if any of the coefficients were statistically equal to zero. These statistics are summarized in Tables 36 and 37. For both models the coefficients are statistically valid and are significant at $P \leqslant = 0.05$.

Validation of the models was the next procedure since it was established that each of the models was significant, each having non-zero coefficients. The predicted expansion values were computed for each of the hold-out samples using each of the models. The predicted values were then compared with the observed expansion values for each sample. These comparisons are given for each model in Tables 38 and 39. Using the previously established criteria for overall performance (that of having the highest number of predicted values within ± 10 percent of the observed and having the smallest range in percent variation). Table 40 was constructed for the

Table 35.—Significance evaluation of regression models for expansion

Model	F-value	Significance probability (Pr>F)	Coefficient multiple of determination (R^2)	Regression mean square (MSR)	Error mean square (MSE)	Degrees of freedom for MSE
(1) PROTEIN KOH	50.37	0.0001	0.56	12.62	0.25	80
(2) PROTEIN KOH HOHR	35.85	0.0001	0.58	8.71	0.24	79
(3) AMYLOSE PROTEIN TYPE	41.70	0.0001	0.61	9.25	0.22	79
(4) AMYLOSE PROTEIN HOHR TYPE	32.20	0.0001	0.63	7.13	0.21	78

Table 36.—Parameter estimates for expansion Model 1

Parameter	Estimate	T* statistic	Probability of T
INTERCEPT	9.87	19.02	0.0001
PROTEIN	−0.28	−4.82	0.0001
KOH	−0.27	−8.63	0.0001

Table 37.—Parameter estimates for expansion Model 2

Parameter	Estimate	T* statistic	Probability of T
INTERCEPT	7.74	6.26	0.0001
PROTEIN	−0.29	−5.03	0.0001
KOH	−0.29	−8.96	0.0001
HOHR	0.22	1.89	0.0624

four expansion regression models. From this table, it can be seen that model 2 best fits the criteria for the best model generated.

$$\text{EXP} = -0.37^* \text{ PROTEIN} - 0.68^* \text{ KOH} + 0.14^* \text{ HOHR}.$$

Thus, from the standardized coefficients, it can be seen that the effect of alkali spreading value is about twice that of protein, and the contribution of the rough rice moisture content effectively cancels half the contribution of protein content.

With an R^2 value of 0.58, the model is fairly strong, accounting for 58 percent of the variation of expansion. The model correctly predicted the expanded or puffed volume increase to within ± 15 percent for 93 percent of the hold-out samples, supporting the validity of usefulness of this model.

Table 38.—Validation results for expansion Model 1

Sample number	Observed expansion	Predicted expansion	Difference	Percent difference
11	5.6	6.28	−0.68	−12.14
13	6.3	5.91	0.39	6.22
14	5.4	5.73	−0.33	− 6.11
22	6.1	6.32	−0.22	− 3.57
23	6.0	5.15	0.85	14.13
24	5.3	6.15	−0.85	−16.04
27	5.2	6.44	−1.24	−23.81
30	6.2	5.73	0.47	7.58
35	6.6	6.20	0.40	6.00
42	5.7	5.89	−0.19	− 3.30
43	5.7	5.54	0.16	2.74
49	5.4	5.43	−0.03	− 0.59
52	5.8	5.77	0.03	0.55
53	6.2	6.01	0.19	3.07
55	5.5	6.13	−0.63	−11.49
56	5.6	6.12	−0.52	− 9.32
60	6.4	6.87	−0.58	− 9.03
62	7.2	7.06	0.14	1.92
67	7.9	6.65	1.25	15.80
71	7.2	7.29	−0.09	− 1.19
72	6.9	7.37	−0.47	− 6.81
82	7.0	6.89	0.11	1.51
87	6.7	5.92	0.78	11.58
89	6.7	6.51	0.19	2.81
93	6.1	6.23	−0.13	− 2.16
96	6.4	6.45	−0.05	− 0.72
100	6.4	6.78	−0.38	− 5.97
102	6.1	6.32	−0.22	− 3.54
105	6.7	6.48	0.22	3.22
110	6.3	6.95	−0.65	−10.32

Table 39.—Validation results for expansion Model 2

Sample number	Observed expansion	Predicted expansion	Difference	Percent difference
11	5.6	6.18	−0.58	−10.38
13	6.3	6.07	0.23	3.62
14	5.4	5.60	−0.20	− 3.72
22	6.1	6.21	−0.11	− 1.80
23	6.0	5.23	0.77	12.84
24	5.3	6.27	−0.97	−18.37
27	5.2	6.36	−1.16	−22.21
30	6.2	5.84	0.36	5.83
35	6.6	6.30	0.30	4.53
42	5.7	5.78	−0.08	1.32
43	5.7	5.58	0.12	2.17
49	5.4	5.64	−0.24	− 4.72
52	5.8	5.84	−0.04	− 0.67
53	6.2	6.16	0.04	0.73
55	5.5	6.22	−0.72	−13.02
56	5.6	6.16	−0.56	−10.02
60	6.4	6.97	−0.57	− 8.94
62	7.2	7.00	0.20	2.75
67	7.9	6.80	1.10	13.98
71	7.2	7.41	−0.21	− 2.86
72	6.9	7.21	−0.31	− 4.48
82	7.0	7.00	0.00	0.00
87	6.7	5.87	0.83	12.38
89	6.7	6.42	0.28	4.15
93	6.1	6.02	0.08	1.31
96	6.4	6.54	−0.14	− 2.12
100	6.4	6.88	−0.48	− 7.56
102	6.1	6.28	−0.18	− 2.89
105	6.7	6.56	0.14	2.02
110	6.3	7.00	−0.70	−11.12

Table 40.—Comparison of validation results for the four expansion regression models

Model	Percent of predicted within ± 10% of observed	Range of percent deviation from observed
1	73.3	−23.81 to 15.80
2	73.3	−22.21 to 13.98

Summary and Conclusions

The work described herein was designed and performed to determine the extent to which various selected endogenous parameters of rice effect the thermal processing behavior of rice. Specifically the objectives were: (1) to measure the values of selected physicochemical properties of a variety of rice samples, (2) to identify as many of those parameters influencing kernel hardness and the puffing of gelatinized rice as possible, and (3) to develop and validate regression equations for the prediction of hardness and the prediction of puffing.

Two empirical models were generated, one for the prediction of kernel hardness, and the other for the prediction of the degree of expansion upon puffing.

To provide enough samples with enough parametric variability to establish statistical credibility, a total of 113 samples were processed and analyzed. These 113 samples were selected from commercial as well as experimental varieties. There were 28 different varieties representing the three grain types, short, medium, and long, taken from four different geographic locations (Louisiana, Arkansas, Mississippi, and Texas), during a 2-year period. All 1980 crop samples were aged at least 4 months prior to analysis, making all samples "aged" samples.

To accomplish the above listed objectives, the rice samples were processed and analyzed under laboratory conditions designed to simulate as closely as possible a typical industrial rice processing environment. The rough rice was hulled, milled, and graded in accordance with U. S. Department of Agriculture guidelines, giving approximately 110 to 150 grams of head rice (whole-kernel rice) for each sampling. The milling yields for each step were carefully noted. The head rice was subjected to physical, mechanical, and chemical analyses.

The physical property of volume was determined by kerosene displacement while length, width, and area were determined by image analysis using a Cambridge Instruments System 23 computerized interactive image analyzer. The mechanical property of hardness was measured by analyzing the yield points of several kernels from each sample on an Instron Universal Testing Machine. The chemical properties of amylose and protein content and alkali spreading value were measured using the standard techniques employed in the rice industry.

Following the analyses, the results were subjected to correlation analysis to establish the bivariate interrelationships among the various parameters. Predictive models for the features (1) kernel hardness, and (2) volume expansion upon puffing were generated by multiple regression techniques using approximately 70 percent of the original number of samples. The models were analyzed for significance and the residuals from the models were analyzed for bias. The models were validated using the remaining 30 percent of the original samples. The ability of each model to predict the appropriate feature was determined by comparing the predicted values with the observed values for each sample.

From the investigation, the following conclusions and observations were made, based on the analyses and observations of the 113 samples used in this study.

1. The long-grain samples from the 113-sample set gave significantly lower yields of head rice than did either the short- or medium-grain

samples.

2. Head rice yield for those samples in this study was found to be significantly correlated in a negative fashion to amylose content ($r = -0.48$), indicating a possible brittleness imparted to the kernel by high amylose content.

3. The hardness of the rice kernel was found to correlate significantly with the area-volume ratio ($r = +0.39$), giving rise to the possibility of strain distribution over the cross-sectional area being important to higher yields.

4. The correlation of parameters with hardness showed that rough rice moisture content correlated negatively with hardness, while protein content and area-volume ratio correlated positively with hardness, and amylose was not found to be significant.

5. A predictive equation for hardness was developed in terms of rough rice moisture content, percent head rice yield, and area-volume ratio, which was able to correctly predict the hardness value of 67 percent of the hold-out samples to within ± 10 percent of the observed value.

6. A new, rapid, and accurate method for determination of rice kernel physical measurements was developed and used in this work.

7. Length-width ratio was found to be highly correlated with grain type ($r = +0.95$) for the samples in this study, substantiating historical data.

8. Type, as manifested by length-width ratio, was found to be highly correlated to amylose content ($r = 0.76$), alkali spreading value ($r = -0.91$), and expansion ($r = 0.65$) for rice samples in this study.

9. The high positive correlation of type with amylose is consistent with the data in that long-grain rice samples had statistically higher amylose values than did medium- or short-grain samples.

10. The high negative correlation between type and alkali spreading value indicates that, for the samples used in this study, the long-grain samples are less porous than the medium- and short-grain samples.

11. The moderately high correlation of length-width ratio with expansion ($r = 0.65$) reflects the fact that long-grain rice samples from this study puffed to a significantly greater degree than did the short- or medium-grain samples. This, in combination with the previous observation leads to the conclusion that degree of kernel porosity probably exerts a significant influence upon the puffability of the rice kernel; i.e., the lower the porosity, to some limit, the higher the degree of expansion.

12. Area-volume ratio, as measured, showed no correlation to kernel porosity.

13. Amylose content was found to be negatively correlated to alkali spreading value, consistent with the previously mentioned correlations of amylose with type and the negative correlation of type with alkali spreading value. This indicates amylose content may be negatively correlated with kernel porosity, which is again consistent since amylose is a linear

molecule and forms tight micellar bundles, whereas amylopectin is branched and tends to form amorphous, porous structures.

14. It was observed that, in bivariate correlation analysis, amylose was significantly related to percent head rice yield ($r = -0.42$), which may assist in explaining the lowered head rice yields of high amylose samples in this study.

15. Protein was found to be significantly lower in the short-grain varieties in the sample set than in either the long- or medium-grain varieties. This may not be significant due to the low number of samples that were short-grain types, however.

16. Long-grain varieties in this sample set were found to puff to a significantly greater extent than either short- or medium-grain varieties.

17. Bivariate correlation of expansion with other physicochemical parameters showed expansion to be positively correlated with amylose ($r = 0.4$) and negatively correlated with alkali spreading value ($r = -0.66$).

18. Multiple regression showed amylose to be negatively related to expansion, and with the inclusion of more than two terms or variables, alkali spreading dropped out, indicating that when several variables are acting together, the partial contribution of each to the overall effect (expansion) may be greatly altered or changed from those effects when the variables are acting totally independently.

19. A regression model for the prediction of expansion of gelatinized rice was developed that accurately calculated the degree of puffing within ± 10 percent of the observed value for more than 70 percent of the samples used for validation. The regression model (EXP=7.74−0.29*%Protein−0.29*KOH value + 0.22*%HOHR) accounted for nearly 60 percent of the variation in the dependent variable, expansion.

20. Biological systems are very complex, and modeling such systems is difficult. It is an arduous task to identify the possible variables or parameters that influence the behavior of biological systems. This study has been a beginning. Puffing has been described in terms of the protein content, porosity, and rough rice moisture content of the rice kernel. An alternate description can be made in terms of the amylose and protein contents, and the grain type.

In conclusion, it can be stated that for the samples used in this study, long-grain samples categorically expanded to a greater extent upon puffing than did either medium- or short-grain samples. However, samples from three varieties of medium-grain rice, Nato, Brazos, and Vista, expanded comparably to the long-grain samples. This fact, coupled with the higher yields from medium-grain varieties, maintains the incentive for farmers to continue offering these and other medium-grain varieties for industrial utilization. The good performance of these and possibly other medium-grain varieties, coupled with their slightly lower cost per pound than long-grain varieties, maintains the incentive for industrial buyers to keep buying medium-grain rice.

Additionally, it was observed that even though long-grain varieties tended to puff into larger kernels than did medium-grain varieties, the puffed long-grain kernels were tougher to chew (had a coarser texture) than were the puffed medium-grain kernels. This was also observed by Juliano et al. (*19*) and Roberts et al. (*32*).

Finally, to determine if the coefficient of multiple correlation could be enhanced, the samples were segregated according to grain type. Correlation and multiple regression analyses were performed on each group. Review of these results indicated no gain in model performance as measured by increase in coefficient of multiple determination or by increase in ability to more accurately predict the expansion values of the holdout samples.

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